Coupled Ocean-Atmosphere Dynamics and Predictability of MJO's

Ragu Murtugudde
Earth System Science Interdisciplinary Center
University of Maryland
College Park, MD 20741
phone: (301) 314-2622 fax: (301) 405-8468 email: ragu@essic.umd.edu

Hyodae Seo
IPRC/University of Hawaii
Honolulu, HI 96822
phone: 808-956-9054 fax: (808) 956-9425 email: hyodae@hawaii.edu

Markus Jochum
National Center for Atmospheric Research
Boulder, CO 80305
phone: (303) 497-1743 fax: (303) 497-1324 email: markus@ucar.edu

LONG-TERM GOALS

Our long-term goal is to develop a coupled ocean-atmosphere model that has significant and quantified skill in predicting the evolution of Madden-Julian Oscillations (MJO's), which is highly relevant to ONR long-term objectives. This requires developing a better understanding of the sensitivities of the atmospheric circulation associated with MJO's to small-scale SST anomalies, regional-scale SST anomalies, the diurnal cycle, surface waves, upper-ocean mixing, and various other aspects of ocean-atmosphere feedbacks.

OBJECTIVES

The objectives and immediate scientific goals of the proposed research are:

1. *Develop and test the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model for MJO predictability and feedback process studies;*
2. *Develop and test a WRF-ROMS regional coupled model for MJO predictability and feedback process studie;*
3. *Test the NCAR CCSM coupled model for MJO predictability and in feedback process studies.*

APPROACH

We are working as a team to study MJO dynamics and predictability using several coupled models in the Indo-Pacific sector as team members of the ONR DRI. This is a fundamentally collaborative proposal that involves Murtugudde, Seo, and Jochum as well as Dr. Arthur J. Miller of the Scripps

	Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Coupled Ocean-Atmosphere Dynamics and Predictability of MJO's**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Maryland,Earth System Science Interdisciplinary Center,College Park,MD,20741**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Institution of Oceanography, UCSD, and Dr. Duane Waliser of JPL/UCLA. The results presented here include work by all the team members and their post-docs (including Dr. John Strack, UMd; Dr. Lei Zhou, Columbia) and students (including Mr. Aneesh Subramanian, SIO; Mr. Ankur Gupta, SIO) because we have discussed, instigated and synthesized each others' research activities and results by keeping in close contact via email and by meeting at various conferences during the past year. Additionally, through Waliser's role as co-chair of both the WCRP-WWRP/THORPEX YOTC Science Team and the MJO Task Force (www.ucar.edu/yotc/mjo.html), we work to leverage from those activities as well as to make sure our research outcomes are positioned to contribute to the overall objectives of those programs.

The primary questions we are addressing are:

1) Do the effects of mesoscale SST on the surface fluxes of heat and momentum introduce significant changes in the amplitude, structure, wavenumber and frequency of the MJO's?

This can be addressed by running models in both coupled and uncoupled mode and comparing the structures of the MJO's produced. Our theoretical work with a linear, barotropic, coupled model (Zhou and Murtugudde, 2009) demonstrates that the coupled system can respond to mesoscale SST anomalies indicating that high resolution coupled models may be crucial for answering this question accurately. The focus here is on how oceanic mixed layer coupling with the atmospheric boundary layer transfers heat and energy to the overlying large-scale atmospheric MJO dynamics, and then on how changes to the mixed layer induced by diurnal cycle forcing and surface gravity wave processes alter these effects.

2) What are the consequences on the predictability of regional MJO development when mesoscale ocean-atmosphere coupling is allowed to influence the evolving MJO?

Does the intrinsic variability (e.g., atmospheric storms) in the domain increase with these mesoscale feedbacks present, thereby lowering the predictability of MJO regional response? Or do the boundary conditions and large-scale dynamics of MJO strongly control the regional response? These uncertainty issues can be quantified by comparing sensitivities to initial conditions, boundary conditions, and physics parameterizations using models in coupled versus uncoupled mode and in high-resolution versus coarse-resolution mode, for both perfect model experiments and runs compared with observed events.

WORK COMPLETED

Since the start of this current award in spring, 2010, we have contributed to the following subset of accomplishments of the multi-institutional team:

a. Constructed a regional version of SCOAR (RSM-ROMS) in the Indo-Pacific sector (led by Seo, UH)
b. Constructed a regional version of WRF in the Indo-Pacific sector (led by Strack, UMd, and Murtugudde, UMd)
c. Run and analyzed SCOAR for several years to determine how well MJO's are simulated. (led by Seo, UH and Gupta, SIO)
d. Run and analyzed WRF-ROMS for several years to determine how well MJO's are simulated (led by Strack, UMd, and Seo, UH)

e. Run and analyzed CCSM4 to determine how well MJO's are simulated (led by Subramanian, SIO, Jochum, NCAR, and Miller, SIO)

f. Tested the sensitivity of CCSM3 to convective parameterizations (led by Zhou, Columbia, and Murtugudde, UMd)

g. Conducted teleconference group meetings with the MJO Task Force (TF), refined the near-term objectives of that activity, and in June 2010 held a TF meeting and co-organized an MJO workshop joint with the CLIVAR Asian-Australian Monsoon Panel (led by Waliser, UCLA/JPL)

RESULTS

SCOAR and RSM MJO modeling

Initial sensitivity tests were performed using the Regional Spectral Model (RSM) for the period of 20OCT2009-20DEC2009, which is one of the six strong MJO events identified during YOTC period. The results from the experiments with 50 km horizontal resolution of the regional coupled model will be eventually compared with the other high-resolution global models for this 6 period of MJO events. The initial goal of the tests is to find the optimal model parameters for physical process (e.g., parameterization for convection and cloud) as well as the intensity of the interior nudging implemented in RSM. Some preliminary results from the coupling with ROMS at the same horizontal resolutions are also provided.

Fig. 1 shows the variance of outgoing longwave radiation (OLR) from NCEP2 on the model domain that covers the entire Indian and Pacific Ocean. On this large domain, despite the weak impact from specified lateral boundary conditions, the solution would be sensitive to intensity of the interior nudging of temperature and wind implemented in the regional models (Kanamaru and Kanamitsu, 2008). It is hence important to perform the test runs with varying intensity of nudging.
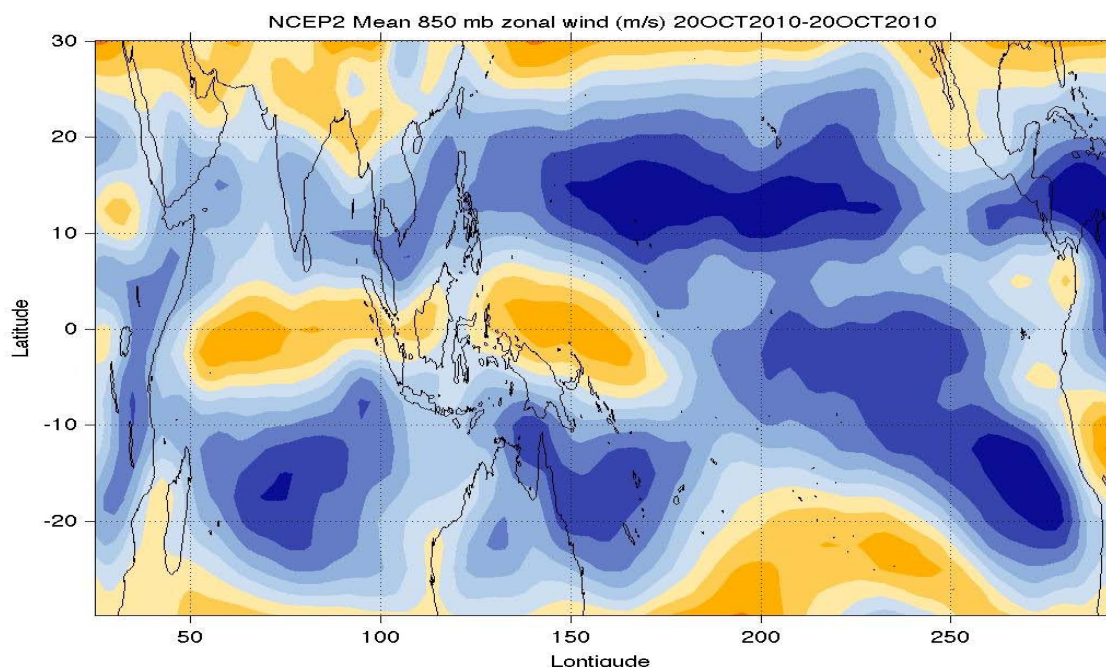

Figure 1. Variance of OLR from NCEP2 (20OCT2010-20DEC2010) on the SCOAR model domain. The horizontal resolution of the atmosphere and ocean model is 50 km, which are coupled at 1hrly frequency.

We have first run the simulation for the period mentioned above with a standard interior nudging scale of L=1000 km, which then are compared with runs with larger nudging scale (weaker nudging) of MJO (L=13,000km) and no nudging (L=0). Fig. 2a and 3a show the lag-longitude correlation of OLR and 850 mb zonal wind (U850) with the OLR at 90E-0N from NCEP2 (This is Level 1 MJO diagnostics, Waliser et al. 2009). Note that representation of MJO propagation during this period in NCEP2 is in reasonable agreement with ERA40 (not shown), although the higher-resolution ECMWF analyses at 25km resolution are known to capture the MJO characteristics much better. This high-resolution ECMWF analysis (from www.ucar.edu/yotc) will be used for model initialization for future simulations.

NCEP2 shows alternating anomalies in convection and zonal wind originating in the western tropical Indian Ocean and subsequently propagating eastward. The large model domain is important for capturing the entire MJO life cycle from the western Indian Ocean to the eastern Pacific, so the proposed domain is well justified. With nudging scale L=1000km (Fig. 2b,3b), RSM produces realistic positive/negative phases of convective and wind anomalies, which propagate eastward in a similar manner to NCEP. Note however that, with weak (L=13000km, Fig. 2c,3c) or no nudging (L=0km, Fig. 2d,3d), RSM is not able to sustain significant MJO characteristics provided from the initial condition.

Note also that, with the strong nudging (L=1000km), we see no significant differences in simulated MJOs due to the different convection and cloud water schemes, which are highly relevant physical parameterizations for simulating MJOs. The current experiments use Kain-Fritsch convective parameterization (Kain, 2004) and a simple RH-based cloud scheme (Slingo 1989). Using the Relaxed Arakawa-Schubert (RAS) scheme and Simplified Arakawa scheme (SAS) for convection and switching to a more complicated cloud water scheme based on RH and cloud water content (Hong et al. 2004) did not make a noticeable differences in MJOs propagation compared to Fig. 2b,3b (not shown). This does not mean that choice of such parameterizations is not important, rather it implies that nudging has the dominant impact on the simulated MJO.

We also performed the RSM-ROMS coupled run at 1hr coupling frequency to test the role of the ocean in MJO. With the strong nudging (Fig. 2e,3e), MJO characteristics are similar to the atmosphere-only run (Fig. 2b,3b), indicating that the nudging still plays a dominant role in MJO simulation. Note also that when RSM with weak nudging is coupled to ocean (Fig. 2f,3f), the overall simulated MJO patterns again resemble the uncoupled run (Fig. 2c,3f), namely weak intraseasonal variability. The coupled experiments hence suggest that, in order to study the role of ocean-atmosphere interactions in MJO simulation and predictability, it is important to produce the realistic MJO characteristics first in the atmospheric model (Woolnough et al., 2007, Vitart et al. 2007).

WRF MJO modeling

A test run using the Weather Research and Forecasting (WRF) Model with the similar setup as RSM is also provided for comparison. The goal of the WRF experiments is to compare the performance of these two credible regional atmospheric models in terms of the simulation of MJOs with as similar model setup as possible. A dominant role by interior nudging in RSM is somewhat consistent with the results from WRF simulation (Fig. 4). The results from the WRF shows that especially the rainfall and U850 are better simulated when the interior nudging is employed compared to the case where no nudging is used. Nevertheless, we noticed that the no-nudging run shows a more reasonable U850 pattern than RSM (Fig. 3c vs Fig. 4f). We are currently investigating in more details the reasons for similarity and dissimilarity btween the model simulations of RSM and WRF, which will then be
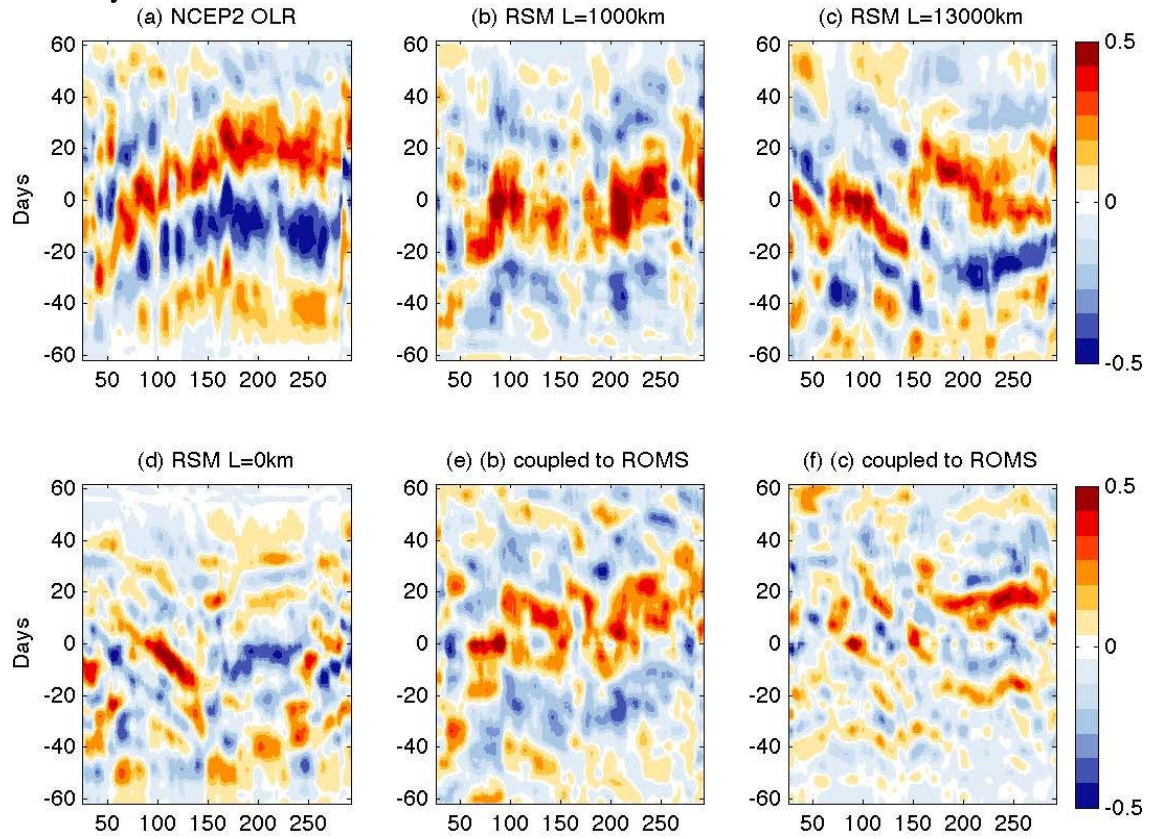
4

coupled to study the MJO-ocean interactions.

Figure 2. Lag-longitude correlation of OLR from each experiment with the variability of OLR at (90E, 0N).
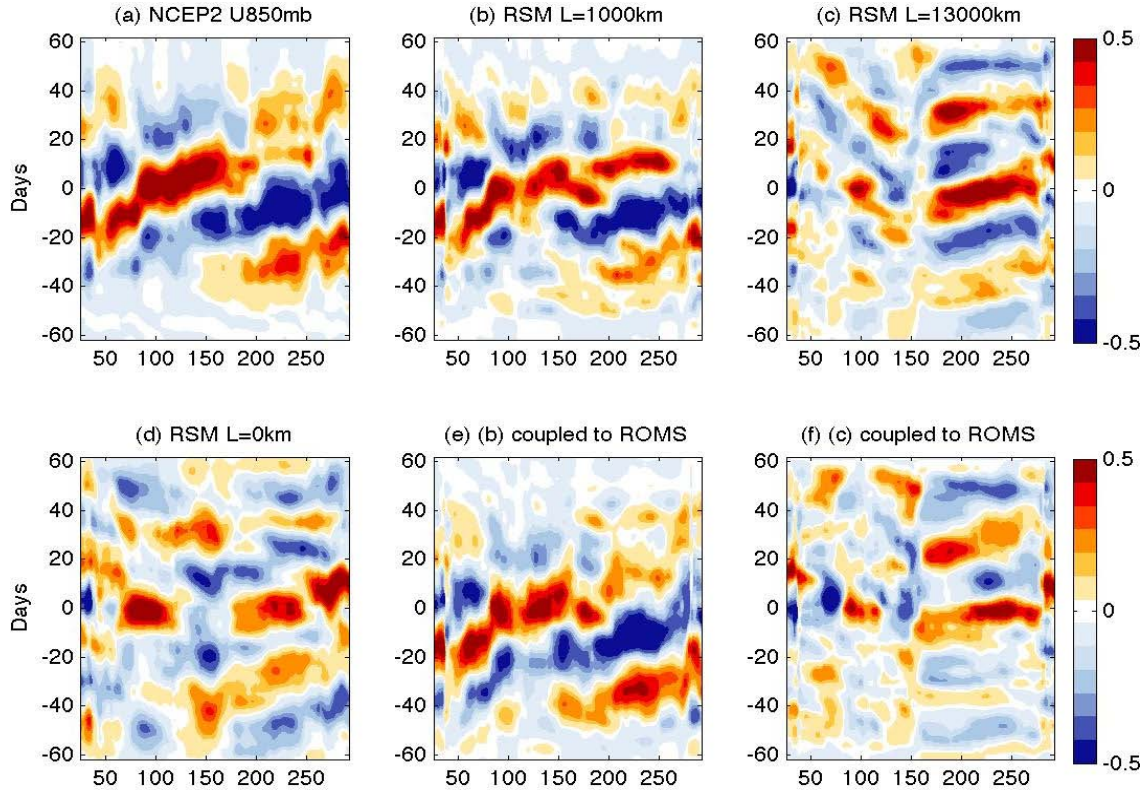
Figure 3. Same as Figure 2 but 850mb zonal wind.

CCSM MJO modeling

The characteristics of MJO's in CCSM were studied in two tracks. The first is geared to understand the behavior of MJOs during high and low ENSO variability decadal regimes. The second is geared to test the sensitivity of MJO's in CCSM to improvements in the fidelity of the convection parameterization.

a. Sensitivity to High and Low ENSO variability in CCSM4

We address whether the characteristics of MJOs in these high and low ENSO regimes differ fundamentally and if this would feedback on the nature of ENSO variability. We also intend to compute the energy budget for the MJOs evolving during these time periods and find sources and sinks of energy for MJOs in the model. According to the energy equation, the three main sources for the perturbed kinetic energy are perturbed potential energy, mean kinetic energy and the heat flux from the sea surface. We will compute this to check for energy sources and sinks in the model.
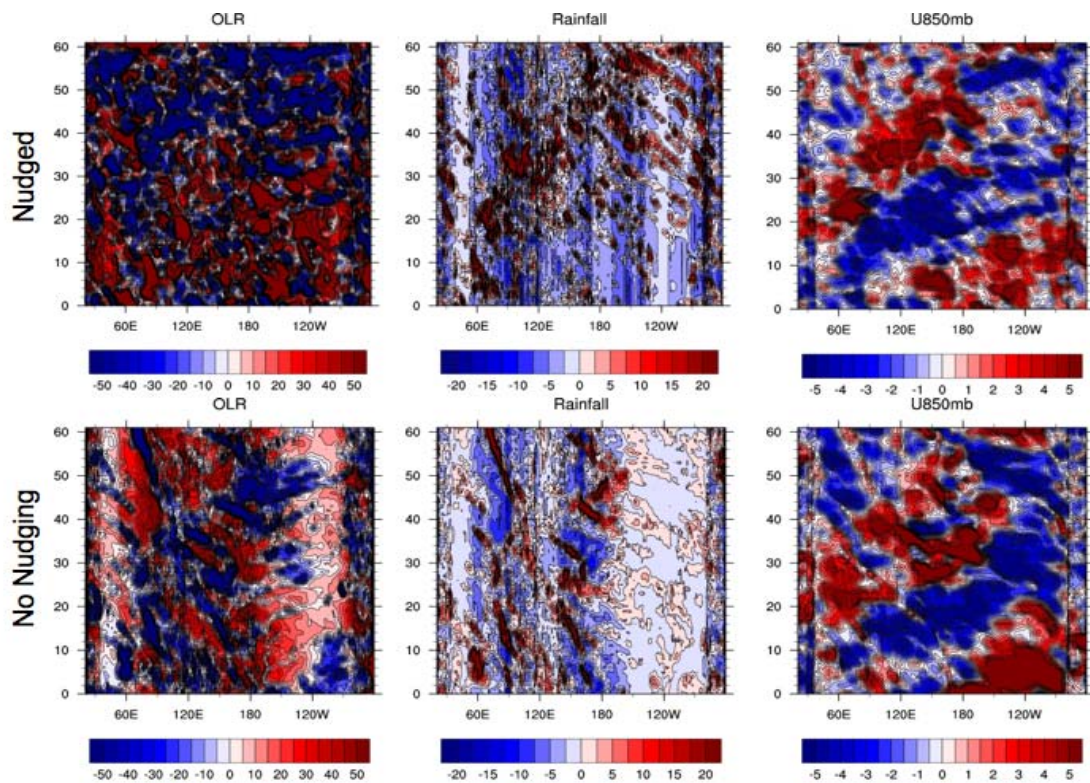
6

Figure 4. Longitude-time diagrams from WRF runs showing (left) OLR, (middle) rainfall, and (right) U850mb. The top panel shows the results from the run with interior nudging and the bottom panel shows the run without the nudging.

We computed a Nino3.4 index from a 500-year CCSM4 archive run. We then selected two ten-year periods, one with the lowest ENSO variability and the other with highest ENSO variability. CCSM4 was reinitialized from the archived CCSM4 for these periods (perfect restarts) and sampled at 1-day intervals in order to explore the high frequency content in CCSM4, which is not saved in the monthly datasets archived at NCAR.

We did initial comparisons of background state during the two regimes in the model and compared them to observed climatology. We also did further analysis to study the nature of MJOs in the two simulations and compare the energy and the properties of MJOs in the two regimes. Comparing the mean zonal 850 hPa winds in NCEP (observations) to the mean zonal 850 hPa winds for the two 10 year periods of low and high ENSO variability periods reveals that the model simulations are comparable to the observed winds from NCEP with mean easterlies in the Pacific and westerlies over the Maritime continent.

The 20-100 day variance of the zonal 850 hPa winds and OLR in NCEP was also comparable to that of the two model simulations (Low ENSO and High ENSO), although the high ENSO time period exhibited somewhat higher levels. Hofmuller diagrams (Fig. 5) reveal the propagation of MJO signals in both model cases and observations. The intensity of MJO's tends to be higher in the high ENSO case. Strong events appear to be sustained and propagate around the globe. Also seen is the weakening of the MJO events over the Maritime continent and strengthening in the Pacific.
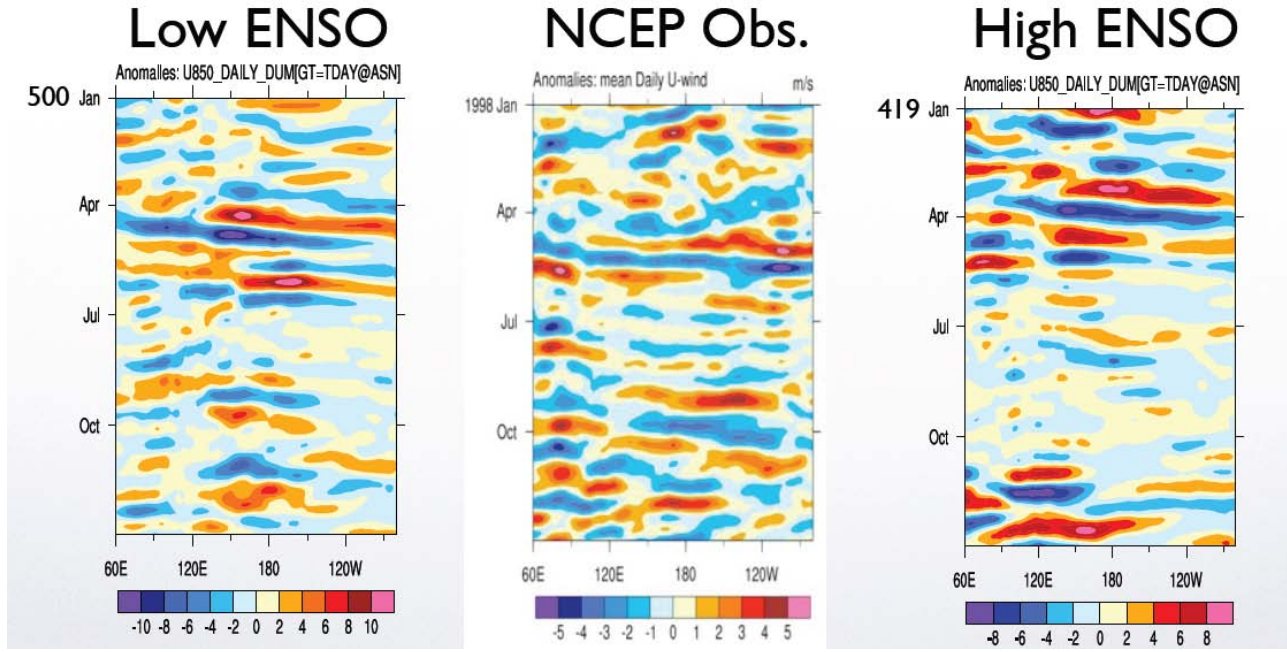
7

Figure 5. Hovmoeller diagram showing propagating intraseasonal bands of zonal 850 hPa wind anomalies for one year in the Low ENSO run (left), NCEP Observed winds (center) and High ENSO run (right).

Power spectra of zonal 850 hPa winds in the Indian Ocean (top three plots) and Western Pacific (bottom three plots) show peaks and hence energy in the intraseasonal bands. The MJO composite index for both runs, with the line marking the threshold value of 1, is also drawn. Periods with the index value greater than 1 are identified as MJO events according to convention. (Wheeler and Hendon, 2004, Waliser et al., 2008)

Power spectra of the wavenumber-frequency characteristics of CCSM4 MJO's (Fig. 6) show that MJO energy is present in low (1 - 3) zonal wavenumbers in the time periods of 30-80 days (following the MJO diagnostics of Waliser et al., 20008) marked within the dashed lines for both model cases and in observations. But there tends to be more energy in the higher frequencies in the low ENSO period.

In addition to single variable spectral calculations in wavenumber-frequency space, cross-spectral calculations were computed to quantify the coherence and phase relationships between different variables. Fig. 7 shows the coherence squared and phase between equatorial OLR and 850-hPa zonal winds for both symmetric and antisymmetric components of the two fields (Hendon and Wheeler 2008). The symmetric component of a variable F is defined as $Fs(f) = [F(f) + F(-f)]/2$, and the antisymmetric component is defined as $Fa(f) = [F(f) - F(-f)]/2$, where f is latitude (Wheeler and Kiladis 1999). Cross spectra are calculated using data during all seasons on 256-day-long segments, with consecutive segments overlapping by 206 days. Prior to forming coherence squared, the symmetric and anti- symmetric powers and cross powers are computed at each symmetric and antisymmetric latitude 0-10 deg and then averaged. Colors in Fig. 7 represent coherence squared between OLR and 850-hPa wind, and vectors represent the phase by which wind anomalies lag OLR anomalies, increasing in the clockwise direction. As has been described in the literature (e.g., Zhang et al. 2006), climate models have trouble simulating this high degree of coherence and ~5-day phase lag between convection and winds that is observed.
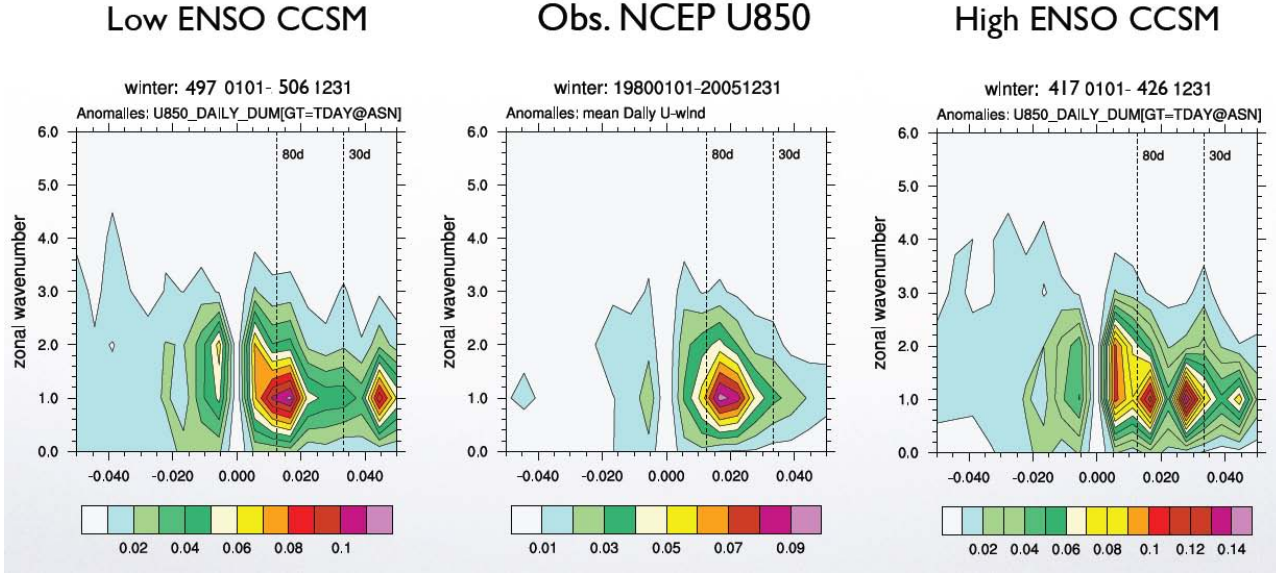
8

Figure 6. 2-D power spectra of zonal 850 hPa winds, with frequency on the x-axis and zonal wavenumber on the y-axis for each model case and observations.

In summary, CCSM4 has relatively strong 20-100 day variability MJO-like events, with relatively faster propagation speeds than observations. This may be due to the background wind fields as cited in other studies. MJOs during High ENSO periods tend to persist over the Tropical Pacific for longer and are more frequent.

*b. Sensitivity to Convection Parameterization in CCSM3*

Two modifications are made to the deep convection parameterization in the NCAR Community Climate System Model, version 3 (CCSM3); a dilute plume approximation and an implementation of the convective momentum transports (CMT). These changes lead to significant improvement in the simulated Madden-Julian Oscillations (MJOs).

Due to the dilute plume approximation, the environmental air is entrained into the cloud at all levels, not only at the cloud top. As a result, the phase relations between the convective heating and the temperature perturbation are modified. Consequently, more available potential energy is generated and the intraseasonal variability (ISV) becomes stronger.

With the CMT, the mean low-level westerly winds over the Indian Ocean and the western Pacific Ocean become stronger and more realistic, while other mean states in the model are not significantly influenced by the modifications to the deep convection parameterization. The organization of ISV is improved, which is manifest in coherent structures between different MJO phases and an improved simulation of the eastward propagation of MJOs with a reasonable

9
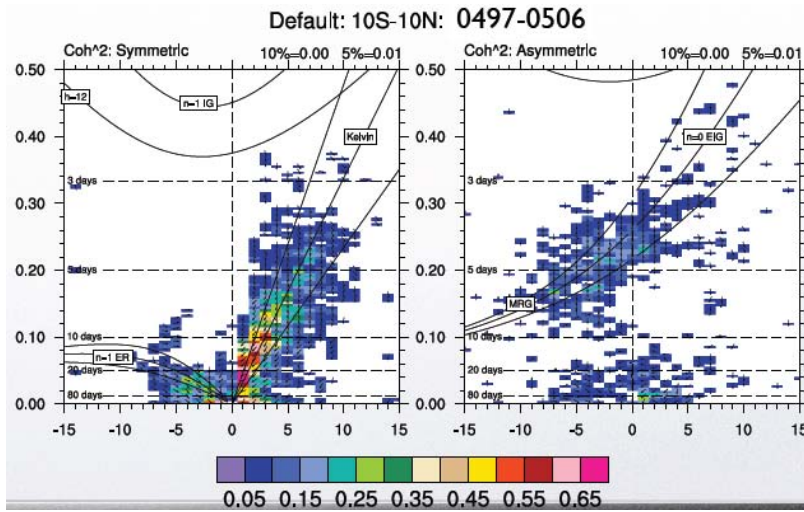
High ENSO CCSM4 Case
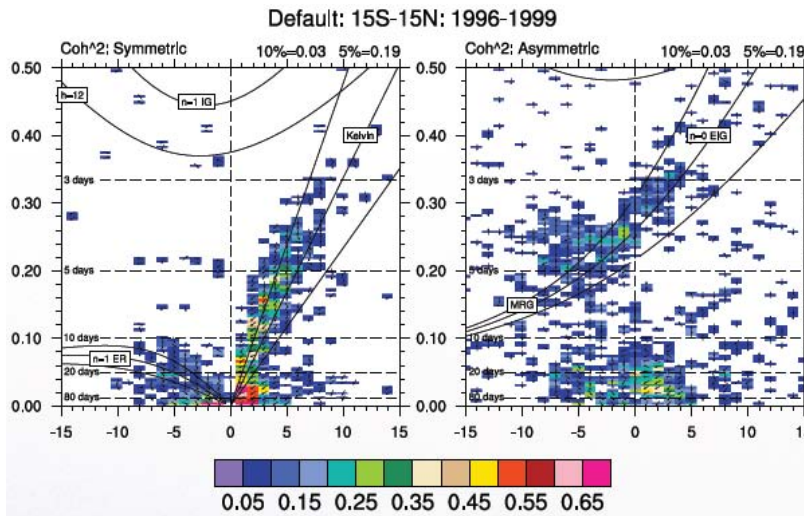
NCEP Observations
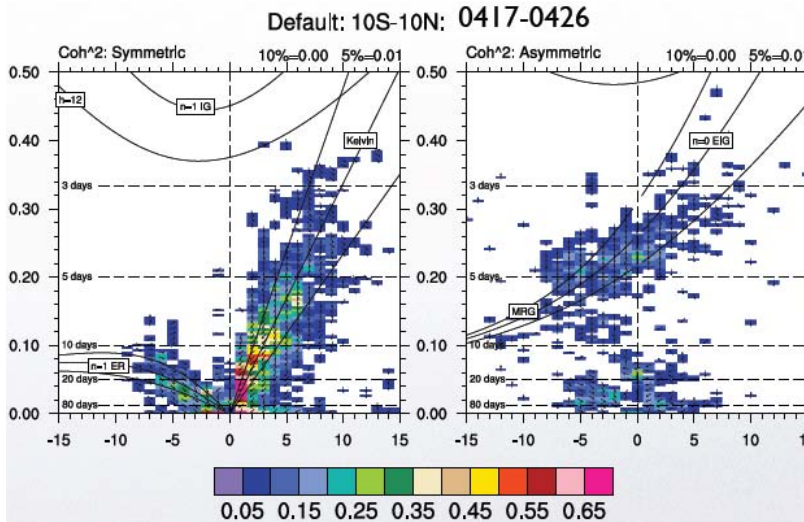
Low ENSO CCSM4 Case

Figure 7. Coherence of U850 and OLR for cross-spectral calculations in frequency-wavenumber space for (top) low ENSO CCSM4 case, (middle) NCEP obs, and (bottom) high ENSO case for both symmetric (left) and antisymmetric (right) components.

eastward speed (Fig. 8). The improved propagation can be attributed to the better simulation of the background zonal winds due to the inclusion of CMT. The selection of the eastward propagation speed of MJOs is also found to be closely related to the mean westerly wind speed.
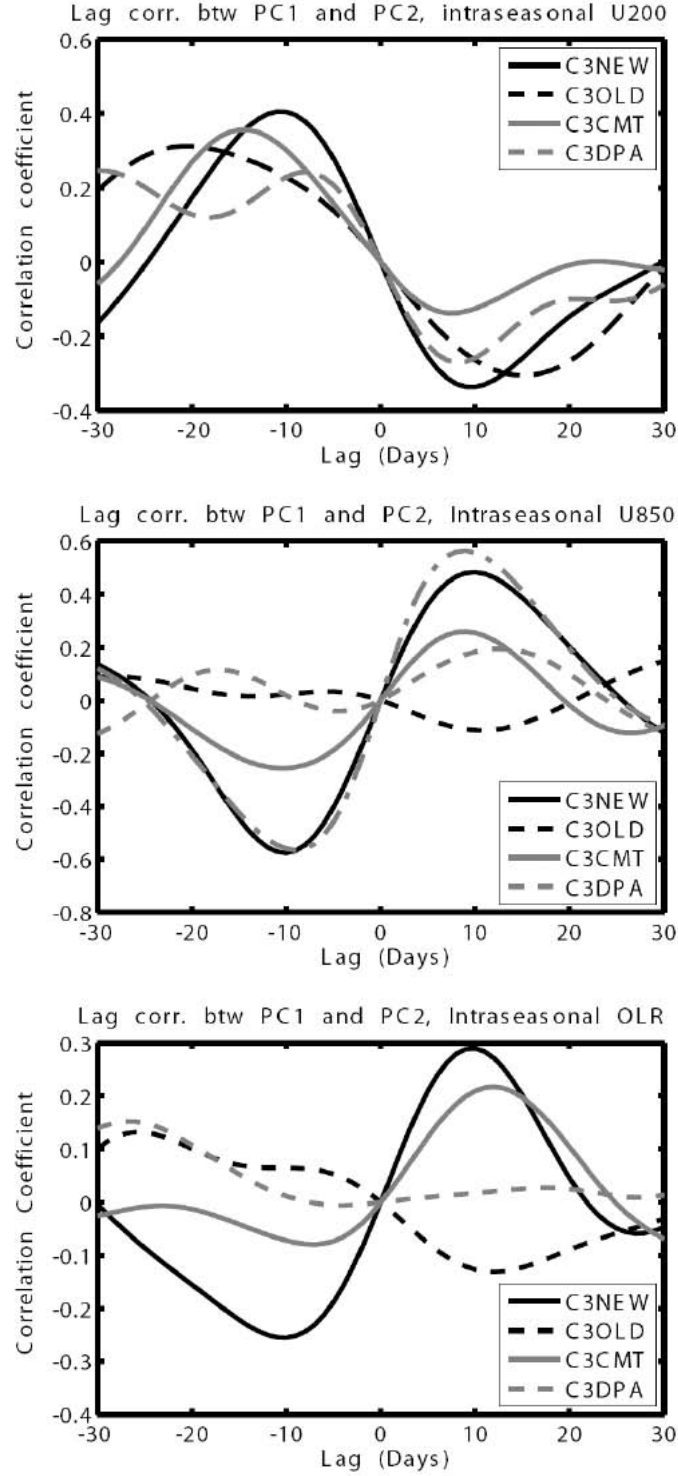

Figure 8. Cross-correlations between PC1 and PC2 of the intraseasonal zonal winds at 200 hPa, at 850 hPa, and intraseasonal OLR anomalies. Cross-correlations between RMM1 and RMM2 defined in Wheeler and Hendon (2004) are superimposed in the middle panel with a dot-dash line.

We are exploring the idea that the large-scale zonal winds are akin to a selective conveyor belt that facilitates the organization of ISVs into highly coherent structures, which are important features of observed MJOs. This study provides evidence for the interaction between the large-scale background state and the ISVs and concludes that it is necessary to consider MJOs in a multiscale framework to enhance their understanding. The conclusions are supported by two supplementary experiments, which include the dilute plume approximation and CMT separately.

IMPACTS/APPLICATIONS

We have discussed our research results with Dr. Mark Swenson, Chief Scientist, FNMOC, to determine how effort might eventually be used to improve forecasting of MJO activity for practical use by the Navy. COAMPS, with specified SST, is currently available for practical regional forecasts. We expect our research to better reveal how ocean-atmosphere mesoscale coupling can influence extended-range (1 week to 1 month) forecasts of MJO variations, what atmospheric convective and SST feedback processes must be included in the model, how strongly oceanic and atmospheric boundary conditions influence the skill of regional MJO forecasts, and what upper-ocean conditions need to be observed to best execute these practical forecasts. As COAMPS soon will also include interactive ocean capabilities with NCOM in real-time mode, our results will additionally provide a comparison to COAMPS skill levels and help point the way in dealing with various regional modeling limitations as well. Extended-range dynamical forecasts in regions influenced by MJO are based on a dynamical process that has potentially useful skill levels. These forecasts are expected to be better than climatology and can contribute to establishing a smart climatology for these regions during times of MJO excitation. This forecast information can then be used in practical Naval operations planning. Dr. Swenson has agreed to continue to discuss our research results in the context of practical usefulness throughout the course of this research.

RELATED PROJECTS

WCRP-WWRP/THORPEX Activities

The MJO Task Force held its first meeting in Busan, South Korea, in June. This was held in concert with a workshop the same week on "Workshop on Modelling Monsoon Intraseasonal Variability" which was co-sponsored by the MJO TF and CLIVAR Asian Australian Monsoon Panel, and hosted by the Asian Pacific Climate Center (APCC). The TF refined and discussed its three major near-term activities:

1) Developing process-oriented diagnostics for MJO model evaluation and improvement,
2) Developing and applying boreal summer MJO diagnostics/metrics in both model evaluation and operational forecast settings, and
3) Improving on the applications and validation activities of the MJO forecast metrics developed by this group's predecessor – the US CLIVAR MJO Working Group (www.usclivar.org/mjo.php).

The MJO workshop was attended by approximately 70 people and was a 3 day event, with oral presentations, poster sessions and significant discussion. A meeting summary for *Bulletin of the American Meteorological Society* is being prepared by Waliser, Wheeler (co-chairs of MJO TF), Hendon and Sperber (co-chairs for AAMP) for submission in November. The meeting workshop page – that includes all talks and posters –can be found at www.ucar.edu/yotc/documents/mjo/KoreaWkshp.html.

In addition to the MJO TF activities, there are two substantive activities within YOTC that are being conducted:

1) Identification of the significant MJO events during the YOTC period (May'08-Apr'10) for use within the YOTC Implementation Plan for a multi-model simulation/forecast activity, and
2) Development of a BAMS article by Waliser et al. that highlights the significant weather/climate events during the YOTC period, expected to be submitted in October.

Note that the present ONR-funded MJO activity is targeting a number of its modeling and analysis activities around the MJO events that occurred during the YOTC period to take advantage of the programmatic synergies and available data sets.

REFERENCES

Hendon, H.H. and M.C. Wheeler 2008: Some space-time spectral analyses of tropical convection and planetary-scale waves. *J. Atmos. Sci.*, **65**, 2936-2948.

Hong, S.Y., J. Dudhia, S.H. Chen SH, 2004: A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Wea, Rev.*, **132**, 103-120.

Kain, J.S., 2004: The Kain–Fritsch convective parameterization. An update. J. Appl. Meteor. 43, 170–181.

Kanamaru, H., and M. Kanamitsu, 2007: Scale-selective bias correction in a downscaling of global analysis using a regional model. *Mon. Weather Rev.*, 135, 334-350.

Slingo, A., 1989: A GCM parameterization for the shortwave radiation properties of water clouds. J. Atmos. Sci., 46, 1419– 1427.

Vitart, F., et al. 2007: Monthly forecast of the Madden Julian Oscillation using a coupled GCM. *Mon. Wea, Rev.*, **135**, 2700-2715.

Waliser, D. E., and 18 co-authors, 2009: MJO simulation diagnostics. *J. Climate*, **22**, 3006-3030.

Wheeler, M.C. and H.H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea, Rev.*, **132**, 1917-1932.

Wheeler, M.C. and G. Kiladis 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber-frequency domain *J. Atmos. Sci.*, **56**, 374-399.

Woolnough, S.J., F. Vitart, and M.A. Balmeseda, 2007: The role of the ocean in the Madden Julian Oscillation: Implication for MJO prediction. *Q. J. Roy. Met. Soc.*, **133**, 117-128.

Zhang, C.D. et al., 2006: Simulations of the Madden Julian Oscillation in four pairs of coupled and uncoupled global models. *Clim. Dyn*. **27**, 573-592.

Zhou, L. and R. Murtugudde, 2009: Ocean-atmosphere coupling on different spatio-temporal scales: A mechanism for intraseasonal instabilities. *J. Atmos. Sci.*, **66**, 1834-1844